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Synthesis of activated 3'-amino-3'-deoxy-2-thio-thymidine, a superior substrate for the nonenzymatic copying of nucleic acid templates†

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We present a scalable synthesis of 3'-amino-3'-deoxy-2-thio-thymidine-5'-phosphoro-2-methylimidazole, an activated monomer that can copy adenosine residues in nucleic acid templates rapidly without a polymerase. The sulfur atom substitution enhances the rate of template copying by 5-fold compared with the 3'-amino-3'-deoxy-T monomer, while the 3'-amino monomers exhibit a 2- to 30-fold enhancement compared with their ribonucleotide counterparts.

Nonenzymatic template-directed replication of nucleic acids has been hypothesized to be the mechanism of information transfer in primitive cells prior to the advent of ribozyme polymerases.¹ Early efforts involving high-energy nucleotide monomers such as 5'-phosphoro-2-methylimidazoles (or 2-MeImpNs) (Fig. 1, top) showed that RNA templates consisting of C residues can be copied by 2-MeImpG in hours to days in the presence of divalent cations (typically Mg²⁺).² However, no enzyme-free process has yet been discovered that enables the rapid and efficient copying of mixed-sequence RNA templates with activated ribonucleotide monomers. This problem has stimulated interest in alternative nucleic acids that might exhibit faster replication chemistry; such polymers are of interest both with respect to the origin of life and in the context of designing artificial life forms based on non-biological chemistry. The most promising non-biological nucleic acids are the phosphoramidate polymers, which are assembled from nucleotides with an amino group on the sugar instead of the less nucleophilic hydroxyl. N3'-P5'-linked phosphoramidate DNA^{3,4} (3'-NP-DNA, Fig. 1, bottom) stands out as an

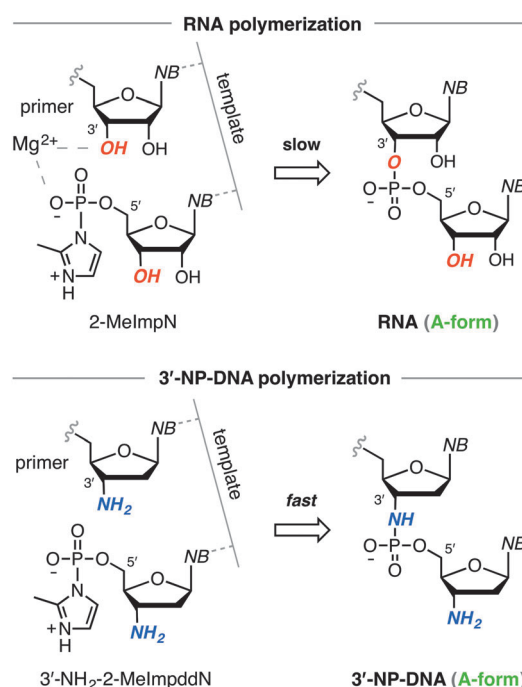


Fig. 1 Template-directed polymerization of RNA (top) and 3'-NP-DNA (bottom). NB denotes nucleobase.

attractive alternative genetic model because it adopts a helical geometry that is similar to that of A-form RNA.⁵ A-form geometry is the preferred conformation for the nonenzymatic template-directed oligomerization of activated ribonucleotides^{6,7} most likely because the A-form double helix of RNA brings the 3'-OH group of the primer in line with the leaving group of the incoming monomer. We have previously shown⁸ that activated 3'-amino-2',3'-dideoxynucleotide monophosphates (3'-NH₂-2-MeImpddNs) (Fig. 1, bottom) rapidly polymerize on short, homopolymeric DNA, RNA, and locked nucleic acid (LNA) templates. We also found⁹ that replacing 3'-amino-T with 3'-amino-2-thio-T enhances the rate and fidelity of 3'-NP-DNA synthesis in the copying of DNA, RNA and 3'-NP-DNA templates. However, further progress in the

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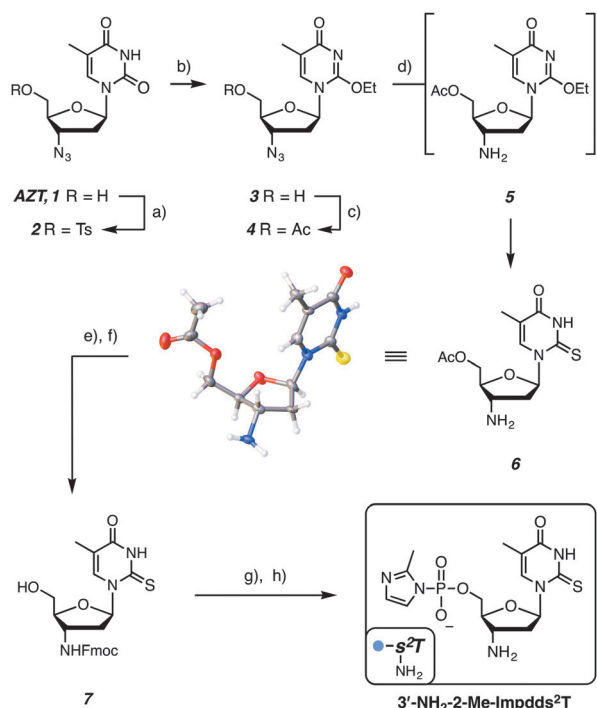
† Electronic supplementary information (ESI) available. CCDC 1440493. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c5cc10317g



development and quantitative analysis of this system has been hindered by lack of access to the critical substrate, the 5'-phosphoroimidazolide of 3'-amino-2-thio-T (3'-NH₂-2-MeImp-dds²T), which could previously be synthesized only in small quantities because of the expensive starting material and the very low yield of the desired product.

Here, we present a concise and scalable synthesis of 3'-amino-2-thio-T and the corresponding 5'-phosphoroimidazolide, 3'-NH₂-2-MeImpdds²T. We also present the first quantitative investigation of template-copying kinetics using this activated nucleotide. Our results show that nonenzymatic 3'-NP-DNA synthesis using the 2-thio modified 3'-amino-T phosphoroimidazolide monomer is significantly faster than with unmodified 3'-amino-T, and is also considerably faster than RNA synthesis with activated U and 2-thio-U.

Our earlier attempts to establish a concise synthetic route to 3'-NH₂-2-MeImpdds²T involved regioselective thio-carbonylation¹⁰ of 4-O-protected 3'-azido-3'-deoxy-thymidine. However, these substrates afforded only deglycosylation products using Lawesson's reagent, an observation later reported¹¹ for 4-O-mesityl-3',5'-di(TBS)-thymidine. We then studied nucleophilic ring opening of 2-thio-2,3'-cyclonucleosides by azides at the 3'-position, but observed little to no conversion (by ¹H NMR analysis) of the substrates in the presence of either excess LiN₃ or TMSN₃ accompanied by various Lewis acids [e.g., Hg(OAc)₂, Er(OTf)₃ and Yb(O-iPr)₃].



Scheme 1 Synthesis of 3'-NH₂-2-MeImpdds²T. Reaction conditions: (a) TsCl, pyr, 0 to 20 °C, 6 h, 73%; (b) DBU, EtOH, 85 °C, 24 h, 81%; (c) DMAP (cat.), Ac₂O, 20 °C, 12 h, >95%; (d) H₂S (gas), TMG, pyr, 0 to 20 °C, 16 h, 53%; (e) 7N NH₃ in MeOH, 20 °C, 92%; (f) Fmoc-OSu, Na₂CO₃ (aq), pyr, 0 to 20 °C, 6 h, 78%; (g) 1. POCl₃, 2,6-lutidine, PO(OMe)₃, 3 Å MS, 0 to 20 °C, 2 h; 2. 2-Me-imidazole, 2 h, 30%; (h) piperidine, DMF, 0 °C, 0.5 h, 85%. X-ray structure: H: white, C: gray, O: red, N: blue, and S: yellow.

Our successful strategy to access 3'-NH₂-2-MeImpdds²T (Scheme 1) commenced with the 5'-tosylation¹² of 3'-azido-3'-deoxythymidine (AZT) **1**.¹³ Intramolecular displacement of the 5'-tosylate by the C2-oxyanion formed in the presence of a Brønsted base (e.g., DBU) yielded the 2,5'-O-anhydro-cyclonucleoside, and subsequent ring-opening in refluxing ethanol afforded the 2-ethoxythymidine **3** in 59% overall yield from **1**. After converting **3** into the acetate **4**, we were able to incorporate the sulfur atom into the nucleobase using H₂S in the presence of tetramethylguanidine (TMG)¹⁴ (see Fig. S1 in the ESI† for details of the reaction setup). ¹H NMR analysis of an aliquot of the crude reaction mixture after 1 hour revealed that **4** was fully consumed, while two new species were formed: 3'-amino-2-ethoxythymidine **5** and 3'-amino-2-thio-thymidine **6**, in a molar ratio of 2:1 (**5/6**). The relative abundance of **6** continued to increase as the reaction progressed [up to ca. 1:3 (**5/6**) after 6 hours]. We did not observe (by either ESI or ¹H NMR analysis) the formation of any 3'-azido-2-thio-thymidine, suggesting that the incorporation of sulfur was slower than the reduction of the 3'-azide, and that **6** was likely formed from **5**. The structure of the 2-thio nucleoside **6** was confirmed by both ¹H-¹H gCOSY NMR spectroscopy and X-ray crystallography (see the ESI†). We then converted **6** into the phosphoroimidazolide precursor **7** via 5'-deacetylation and Fmoc protection of the 3'-amine. A one-flask 5'-O-phosphorylation and 2-methyl-imidazolide synthesis, followed by the removal of Fmoc, provided 3'-NH₂-2-MeImpdds²T in 26% overall yield from **7**.

With 3'-NH₂-2-MeImpdds²T in hand we proceeded to carry out nonenzymatic primer extension experiments to quantitatively interrogate the effect of 2-thio substitution on RNA template-copying rates (Fig. 2). We used a primer/template complex composed of a DNA primer strand ending in a 3'-NH₂-G and a complementary RNA template strand containing a 5'-C₂A₄ overhang. pK_a of the protonated 3'-amine of 3'-amino-2',3'-dideoxy-2-thio-thymidine is 7.5 (see the ESI†), similar to that reported for 3'-amino-2',3'-dideoxy-T (7.7).¹⁵ 3'-NH₂-2-MeImpdds²T tends to undergo intramolecular cyclization due to the proximity of the primary 3'-amine group to the phosphorus electrophile.⁸ Because the half-life (t_{1/2}) of 3'-NH₂-2-MeImpdds²T is 1.2 h⁸ and that of 3'-NH₂-2-MeImpdds²T is 1.3 h (see the ESI† for details) under optimized primer extension conditions [100 mM 1-(2-hydroxyethyl)-imidazole, pH 7.5, 4 °C], we tracked primer extension only up to a maximum of 1 h. We determined observed rate constants k_{obs} for the first step of the primer extension by following the loss of unreacted primer over time (Fig. 2).

At a 10 mM initial concentration of 3'-NH₂-2-MeImpdds²T (Fig. 2, left), k_{obs} of primer extension was 0.42 h⁻¹ (Table 1, entry 1). Notably, 2-thio modification led to about a 5-fold rate enhancement (Fig. 2, right), such that k_{obs} for 10 mM 3'-NH₂-2-MeImpdds²T was 1.92 h⁻¹ (Table 1, entry 2). This increase likely results from the additional stabilization induced into the primer/template duplex afforded by the formation of a s²T:A base pair compared to a canonical T:A base pair,¹⁶ as well as the more 3'-endo-like sugar puckering of 2-thio-nucleotide, which is the favoured sugar conformation in nonenzymatic primer extension reactions.¹⁷ The k_{obs} values for reactions containing the activated ribonucleotides¹⁸ 2-MeImpU, 2-MeImps²U and its ribo-T analog 2-MeImps²T were all



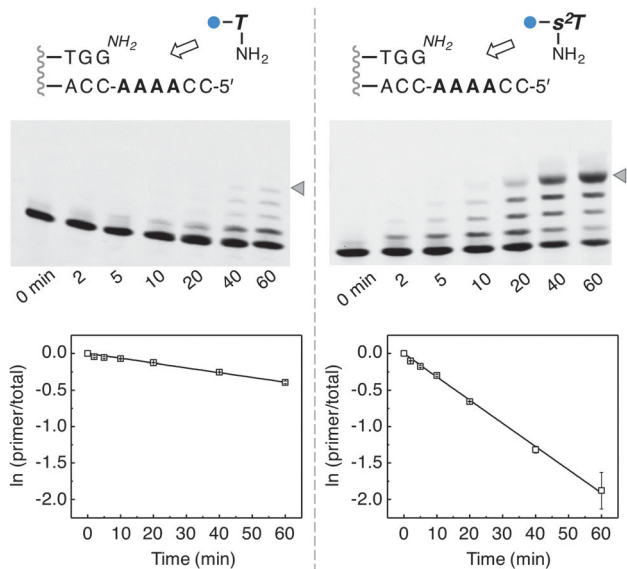


Fig. 2 Kinetics of copying a $r(A)_4(C)_2$ template with 3'-NH₂-2-MeImpddT (left) and 3'-NH₂-2-MeImpdds²T (right), in the presence of 100 mM 1-(2-hydroxyethyl)-imidazole, at pH 7.5 and 4 °C. Reactions were initiated by addition of monomers and monitored by gel electrophoresis. The triangle indicates the primer +4 product. (bottom) Natural log of the fraction of the unreacted primer plotted against incubation time. Errors were based on two experiments. Primer strand (DNA, 0.2 μM): 5'-(FAM)-AGC-GTG-ACT-GAC-TGG-(NH₂)-3', obtained enzymatically in ca. 85% purity based on LC-HRMS (see the ESI†). Primer concentration was corrected for unreactive oligonucleotide impurity. Template strand (RNA, 1 μM): 5'-CCAAAA-CCA-GUC-AGU-CAC-GCU-3' RNA.

Table 1 Reaction kinetics measured for 10 mM T/U monomers at 4 °C

Entry	Template	Monomer	k_{obs} (h ⁻¹)	Relative k_{obs}
1 ^a	$r(A)_4(C)_2$	3'-NH ₂ -2-MeImpddT	0.42 (1)	7
2 ^a	$r(A)_4(C)_2$	3'-NH ₂ -2-MeImpdds ² T	1.92 (2)	30
3 ^b	$r(A)_6$	2-MeImpU	ND	—
4 ^b	$r(A)_6$	2-MeImps ² U	0.064 (1)	1
5 ^b	$r(A)_6$	2-MeImps ² T	0.22 (6)	3

^a In the presence of 100 mM 1-(2-hydroxyethyl)imidazole. ^b Data obtained from ref. 18. Reactions performed with 200 mM MgCl₂ at pH 7.0.

lower than the values for the activated 3'-amino nucleotides described above (Table 1), even though these ribonucleotide polymerizations were assayed in the presence of 200 mM Mg²⁺ to optimize the reactivity. The rate enhancement observed for 2-MeImps²T vs. 2-MeImps²U suggests that methylation at the 5-position of 2-thiouracil leads to stronger monomer–primer stacking. Additionally, primer extension reactions with 3'-NH₂-2-MeImpdds²T are 10-fold faster than with the corresponding ribonucleotide, 2-MeImps²T, presumably due to the greater nucleophilicity of the 3'-amine. Remarkably, combining the effect of the 3'-amine and the 5-methyl groups results in an ca. 30-fold

(Table 1, entries 2 vs. 4) faster reaction. Further physical and kinetic characterization will be required to distinguish the contributions of enhanced monomer binding vs. enhanced monomer reactivity for these observations.

In conclusion, we have developed a scalable synthesis of a 2-thio modified thymidine monomer, 3'-NH₂-2-MeImpdds²T. Our synthetic route provided this highly reactive nucleotide in sufficient amounts to perform quantitative measurements of nonenzymatic RNA template-copying rates for the first time. Our results show that 3'-NH₂-2-MeImpdds²T can polymerize on a DNA/RNA primer/template complex significantly faster than any other U or T monomer that has been reported thus far.

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Notes and references

- M. P. Robertson and G. F. Joyce, *The Origins of the RNA World*, *CSHP Biol.*, 2012, **4**, a003608.
- T. Inoue and L. E. Orgel, *J. Am. Chem. Soc.*, 1981, **103**, 7667.
- W. S. Zielinski and L. E. Orgel, *Nucleic Acids Res.*, 1985, **13**, 2469.
- M. Tohidi, W. S. Zielinski, C. H. Chen and L. E. Orgel, *J. Mol. Evol.*, 1987, **25**, 97.
- V. Tereshko, S. Gryaznov and M. Egli, *J. Am. Chem. Soc.*, 1998, **120**, 269.
- M. Kurz, K. Göbel, C. Hartel and M. W. Göbel, *Angew. Chem., Int. Ed. Engl.*, 1997, **36**, 842.
- I. A. Kozlov, P. K. Politis, A. V. Aerschot, R. Busson, P. Herdewijn and L. E. Orgel, *J. Am. Chem. Soc.*, 1999, **121**, 2653.
- S. Zhang, N. Zhang, J. C. Blain and J. W. Szostak, *J. Am. Chem. Soc.*, 2013, **135**, 924.
- S. Zhang, J. C. Blain, D. Zielinska, S. M. Gryaznov and J. W. Szostak, *Proc. Natl. Acad. Sci. U. S. A.*, 2013, **110**, 17732.
- Y. Masaki, R. Miyasaka, K. Hirai, H. Tsunoda, A. Ohkubo, K. Seio and M. Sekine, *Chem. Commun.*, 2012, **48**, 7313.
- P. C. Tlatelpa and H. Huang, *Tetrahedron Lett.*, 2014, **55**, 4780–4784.
- T.-S. Lin, Z.-Y. Shen, E. M. August, V. Brankovan, H. Yang, I. Ghazzouli and W. H. Prusoff, *J. Med. Chem.*, 1989, **32**, 1891.
- This compound is 200 times cheaper (per 1 gram) than the starting material [5'-O-(dimethoxytrityl)-N³/O⁴-(toluoyl)-2-thiothymidine] that we used for the earlier synthetic route⁵.
- A. Miazga, F. Hamy, S. Louvel, T. Klimkait, Z. Pietrusiewicz, A. Kurzyńska-Kokorniak, M. Figlerowicz, P. Wińska and T. Kulikowski, *Antiviral Res.*, 2011, **92**, 57.
- E. Kervio, A. Hochgesand, U. E. Steiner and C. Richert, *Proc. Natl. Acad. Sci. U. S. A.*, 2010, **107**, 12074.
- A. T. Larsen, A. C. Fahrenbach, J. Sheng, J. Pian and J. W. Szostak, *Nucleic Acids Res.*, 2015, **43**, 7675.
- N. Zhang, S. Zhang and J. W. Szostak, *J. Am. Chem. Soc.*, 2012, **134**, 3691.
- B. D. Heuberger, A. Pal, F. D. Frate, V. V. Topkar and J. W. Szostak, *J. Am. Chem. Soc.*, 2015, **137**, 2769.

